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The effects of biomass binders and moisture content on the mechanical durability of rice husk pellets

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Abstract. Paddy straw and rice husk (RH) are considered agricultural waste. About 22 wt% of paddy is RH, which is normally disposed of by open burning. Pelletizing RH increases the bulk density of the waste and is capable of providing benefits such as ease of transport and potentially a more efficient fuel for combustion. This will allow for RH to be utilized for more meaningful applications instead of just being burnt. However, one of the main challenges of producing RH pellets is their low durability, causing pellets to be broken into fines and dust during transportation and thus making them unattractive to potential buyers. This work aims to investigate suitable locally-sourced biomass waste as binder compounds that could improve the mechanical durability of RH pellets. Here, the effects of binder types, binder contents and moisture contents on RH pellet durability were evaluated. Palm kernel shell (PKS), palm oil mill effluent (POME) and sawdust were selected due to their abundance in Malaysia. In general, it was observed that the mean durability improved as moisture contents increased. More specifically, pellets with PKS and POME binders improved mean durability whereas sawdust deteriorated the durability. The results presented would be beneficial for the improvement of RH pellet production for domestic and export consumptions.

1. Introduction

Aside from solar energy, bioenergy is a major renewable energy resource in Malaysia. Bioenergy accounts for 28.3 % of installed capacity of renewable energy installations in 2018 [1]. One of the bioenergy sources is biomass, which is a large energy resource produced by agricultural activities led by the palm oil and rice industries. A lot of research attention is given to the palm oil industry and the waste it produces as a biomass resource due to Malaysia's leading role in the world market for palm oil. However, as the staple food of majority of Malaysians, rice and its derivative industry also contribute a huge biomass resource potential. In terms of agricultural land use, the rice industry has the third largest planted area in Malaysia after oil palm and rubber in 2018 [2].

Rice husk (RH), which properties are summarised in Table 1, is a by-product of the rice milling process and is produced during the removal of the husk/bran layer to produce white rice. In Malaysia, it is estimated that 0.7 million tonnes of RH was generated from paddy production of 2.6 million tonnes [3]. Previous studies includes RH pellets without binders, binder effects on RH biochar pellets and RH pellets pre-treated with alkali. While there have been studies done on RH pellets, there are still limited studies that are able to characterize durability of pellets made of RH with binder content. The current



work aims to contribute to the understanding of the effect of various binders on RH pellets as there are limited research that explores this specific topic. The most durable RH pellets recorded based on prior research is 96 %, i.e., slightly short of 97.5 % for fines of 2 mm for herbaceous biomass as set in ISO 17225-6:2014. Several suggestions to improve mechanical durability of RH pellets with locally sourced binders that meets the international standard are presented in this work.

Table 1. Properties of Rice Husk [4, 5].

| Components | Content (%) |
|----------------------------|-----------------|
| Cellulose | 28.6 |
| Hemicellulose | 28.6 |
| Lignin | 24.4 |
| Extractive matter | 18.4 |
| Proximate Analysis | |
| Moisture (%) | 7.27 ± 0.08 |
| Ash (%) | 13.7 ± 0.4 |
| Volatile Matter (%) | 73.0 ± 2 |
| Fixed Carbon (%) | 13.3 |
| High Heating Value (MJ/kg) | 15.9 |
| Ultimate analysis | |
| Nitrogen | 0.21 |
| Carbon | 26.69 |
| Sulphur | 0.17 |
| Hydrogen | 2.88 |
| Oxygen | 70.05 |

Improvement of RH pellet durability has the potential to commercialize RH pellet as biomass fuel. This presents business opportunities especially for paddy farmers and rice mill owners. Commercializing RH pellets would add incentive for rice millers and paddy farmers to sell the RH instead of disposing them via open burning, thus having positive impacts on the local economy and environment.

1.2. Potential binders for RH pellet

Some raw materials have sufficient natural binding content in the biomass that quality pellets can be produced without requiring additional binders. For others, binders are required. Binders can be widely categorized into organic and inorganic. Examples of organic binders are starch, alkaline lignin, rapeseed flour, coffee meal, bark, pine cones, lignin powder, crude glycerol, bentonite, lignosulfonate and wood residue. The binding forces can be categorized into five major groups, which are solid bridges, attraction forces between solid particles, mechanical interlocking bonds, adhesion and cohesion forces, and interfacial forces and capillary pressure [6-8].

The contents of a binder are crucial in affecting the quality of the pellet. A review by Kaliyan and Morey [9] found that pellet contents such as starch, protein and lignin enhanced binder characteristics, thus positively affecting the quality of the pellets. On the other hand, fiber and fat oil have the opposite effect onto the pellet durability. Table 2 summarizes the factors and characteristics of binder contents.

The selection of binders should be based on cost and environmental friendliness, thus green wastes are a reasonable approach because of low cost and availability. In the present work, biomass wastes and/or by-products local to Malaysia are investigated. In 2017, Malaysia's highest agricultural crop productions were oil palm fresh fruit bunches (101.7 million tonnes), paddy (2.6 million tonnes), and natural rubber (0.7 million tonnes) [2].

Table 2. Characteristics of binder contents [9].

| Factor | Characteristics |
|------------------------|---|
| Starch | <ul style="list-style-type: none"> • Acts as binder. • High amount positively affects quality. • Adding pregelatinized starch is better than raw starch. |
| Lignin and Extractives | <ul style="list-style-type: none"> • Acts as a binder. • High amount, up to 34%, positively affects quality. |
| Protein | <ul style="list-style-type: none"> • Acts as binder. • High amount positively affects quality. • Adding raw protein better than denatured protein. |
| Fiber | <ul style="list-style-type: none"> • High % of water-insoluble fiber negatively affects quality. • Additives such as lignosulfonate or lime help to increase quality. |
| Fat/Oil | <ul style="list-style-type: none"> • High amount of fat negatively affects quality. |

A screening process was carried out based on composition of biomass residues. Lignin contents were compared between the residues as the main selection criteria as lignin is one of the important binding agents for pelletisation. Table 3 summarises starch and lignin contents of selected biomass wastes that were being considered as binders in this study. From this list, sugarcane's bagasse and 'top and trashier' were the only ones with lignin contents lower than 20%. On the other hand, PKS and POME contained significantly higher lignin as compared with the other residues. Since RH comprised 24.4 % lignin contents, biomass residues with higher lignin contents were shortlisted. From the list, PKS, POME and wood residue contained higher lignin than RH, and thus were chosen for investigation.

Table 3. Composition of biomass residues.

| Biomass Residue | Starch | Lignin | Source |
|------------------------|--------|--------|--------|
| Palm Kernel Shells | ND | 50.7 | [4] |
| Mesocarp Fibers | ND | 27.7 | [4] |
| Empty Fruit Bunches | ND | 22.1 | [4] |
| Palm Oil Mill Effluent | ND | 42.0 | [4] |
| Oil Palm Trunks | 17.2 | 24.5 | [10] |
| Oil Palm Fronds | 3.1 | 20.2 | [10] |
| Oil Palm Leaves | 2.5 | 27.4 | [10] |
| Rice Husk | ND | 24.4 | [4] |
| Rice Straw | ND | 22.3 | [4] |
| Bagasse | ND | 13.8 | [11] |
| Top and Trashier | ND | 8.0 | [11] |
| Wood Residues | ND | 29.0 | [8] |
| Rubberwood | ND | 29.0 | [12] |

2. Methodology

2.1. Raw materials preparation

Figure 1 shows the main raw materials, i.e., RH, PKS, POME and sawdust, used in this work. Rice husk was obtained from a rice mill in Tanjung Karang, Selangor owned by Firma Rena Sdn. Bhd, PKS and POME from a palm oil mill in Tanjung Tualang, Perak owned by Kilang Minyak Sawit Tanjung Tualang Sdn. Bhd., while akasia sawdust from Detik Aturan Sdn. Bhd.

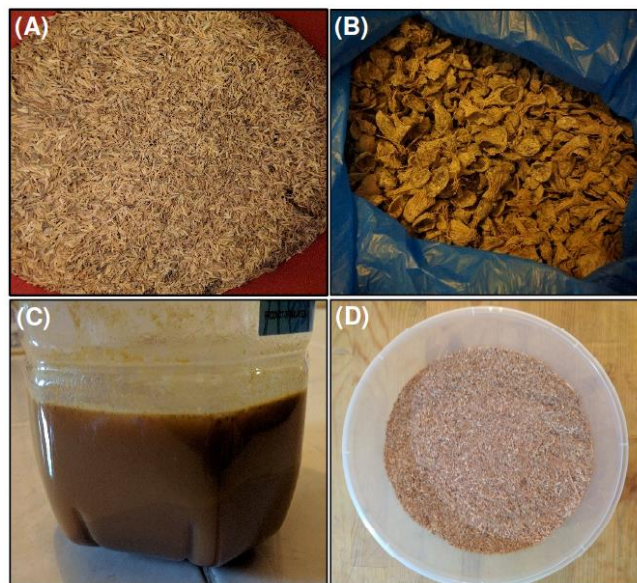


Figure 1. Rice husk (A), PKS (B), POME (C) and sawdust (D).

Both RH and PKS were ground using a cross beater mill, model Fritsch Pulverisette 16, with a 1 mm blade, and subsequently stored in sealed containers at room temperature. Sawdust and POME, in fines and liquid form, respectively, were stored in sealed containers and also at room temperature.

2.2. Design of experiment

Taguchi method offers a systematic approach to determine optimal levels of process parameters. A three-level design with three factors were selected in this work. The three factors selected were binder types, binder contents (%) and moisture contents (%). From the available orthogonal arrays, an L9 that has 9 number of experimental runs, was chosen. The L9 array, binder types, and specific amount of the binder and moisture contents are presented in Table 5 together with the results.

2.3. Preparation of samples

The moisture content of RH, PKS and sawdust were determined in three replicates using an MX-50 Moisture Analyzer, which uses a 400 W straight halogen lamp heating system as the measurement method. Each run requires a sample of 1 kg, and each sample is prepared according to an appropriate mixture. First, binder mass was determined based on mass percentage from 1 kg. The moisture content of the RH was then adjusted to the required level by spraying water and mixing well in a tray. The additional water required to achieve the desired moisture content of the RH was calculated based on the average moisture content of the RH.

2.4. Pellet mill

The pellet mill used in this experiment was a flat ring roller type powered by an 11-kW motor with a capacity of 30 kg/hour. The mill was owned by Forest Research Institute Malaysia (FRIM). There were 230 die holes, each with a diameter of 6 mm and a depth of 25 mm. The samples were fed into the pellet

mill by hand until all 1 kg samples were fully consumed. The formed pellets were then discharged from the mill and into a tray for collection.

2.5. Mechanical durability

The mechanical durability of the pellets was determined according to ISO 17831-1:2015. The pellet tester used in this work belonged to the Universiti Tenaga Nasional (UNITEN), and it was fabricated in accordance to the same ISO standard. Each 50 g sample was prepared by sieving using a 3.15 mm hand sieve to remove fines, manually shaking each test portion in a circular motion. The remaining materials were weighed to determine m_E , which is the mass of the sieved pellets before tumbling treatment. After that, the materials were fed into the pellet tester box, and then tumbled for 10 minutes at a speed of 50 rpm. Finally, the materials were weighed again, this time to determine m_A , which is the mass of sieved pellets after tumbling treatment.

The mechanical durability of the pellets, DU , was then calculated using the formula:

$$DU = \frac{m_A}{m_E} \times 100 \%$$

where DU is the mechanical durability of the pellets (%), m_A is mass of sieved pellets after tumbling treatment (g) and m_E is mass of sieved pellets before tumbling treatment (g)

3. Results and discussion

Preliminary analyses were conducted to characterize the fibre properties of the raw samples and mechanical properties of the pellets. The results were then studied to understand the effects of moisture contents, binder type and binder content to the pellet durability. The fibre analysis of raw samples of RH, PKS and akasia sawdust are listed in Table 4. PKS exhibited the highest lignin content at 41%, which was followed closely by sawdust at 38.1%, and then RH at 21.8%. The content of hemi-cellulose for sawdust was 7.5%, i.e., lower than PKS and RH, which had 17.9% and 19.5%, respectively. The moisture contents for all three samples were about 15%.

Table 4. Fibre analysis and moisture content of raw RH, PKS and sawdust.

| Raw Samples | Lignin (%) | Cellulose (%) | Hemi-cellulose (%) | Moisture Content (%) |
|-------------|------------|---------------|--------------------|----------------------|
| RH | 21.8 | 45.1 | 19.5 | 15.1 |
| PKS | 41.0 | 26.9 | 17.9 | 14.9 |
| Sawdust | 38.1 | 44.8 | 7.5 | 15.0 |

Table 5. Durability based on L9 Taguchi Method.

| Run | Binder Type | Binder Amount | Moisture Content | Mechanical Durability |
|-----|-------------|---------------|------------------|-----------------------|
| 1 | PKS | 0 | 17 | 79.8 |
| 2 | PKS | 5 | 21 | 92.2 |
| 3 | PKS | 10 | 25 | 94.9 |
| 4 | Sawdust | 0 | 21 | 87.9 |
| 5 | Sawdust | 5 | 25 | 91.0 |
| 6 | Sawdust | 10 | 17 | 78.0 |
| 7 | POME | 0 | 25 | 92.4 |
| 8 | POME | 5 | 17 | 92.4 |
| 9 | POME | 10 | 21 | 82.4 |

In general, the mechanical durability (DU) of RH pellets varies from 78.0% (Sawdust/10/17) to 94.9% (PKS/10/25) (Table 5). This variation is attributed to a combination of all three factors. If each factor is analysed individually according to the type of binders, the DU increases with increasing PKS contents and moisture contents. However, this trend is inconclusive for sawdust and reversed for POME as binders. To understand the effect of each factor, the results are discussed separately.

3.1. Effect of binder types and contents

Figure 2 shows the mean durabilities of RH pellets based on binder types, i.e., PKS, POME and sawdust, as compared with RH pellets without binder. Here, RH pellets with PKS demonstrated the highest mean durability at 93.6%, followed by those with POME and sawdust at 87.4% and 84.5%, respectively. In other words, the additions of PKS and POME improved the durability of RH pellet, with PKS exhibiting an improvement of 6.9%, compared with POME which only improved the durability by 0.7%. On the other hand, the addition of sawdust deteriorated the pellet durability by 2.2%.

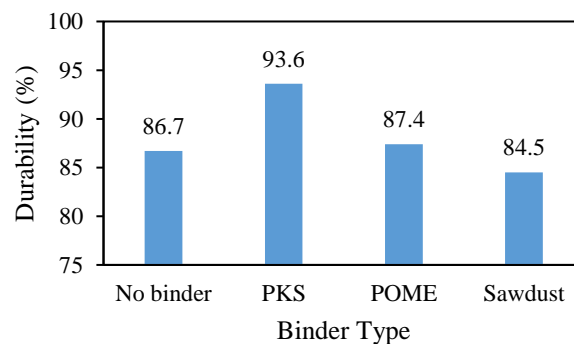


Figure 2. Mean durabilities based on binder types.

In general, RH pellets with 5% and 10% PKS binder contents improved pellet durability (Refer figure 3). The RH pellets with 10% PKS content and 25% moisture content exhibited the highest durability at 94.9%. This was achieved because of the higher lignin content of PKS (41%) as compared with RH's 21.8%. The additional lignin improved the binding process as it was softened by heat and glued the RH during pelleting [9].

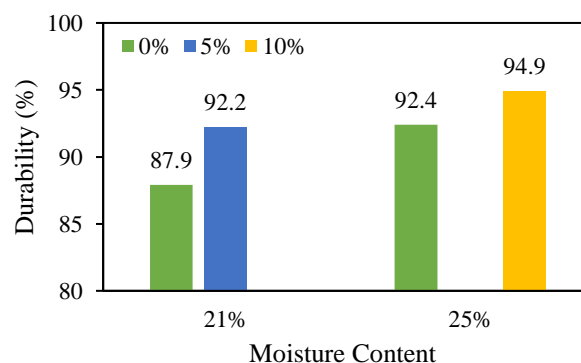


Figure 3. Durability comparison with and without PKS.

Figure 4 shows that RH pellets with sawdust binder deteriorated pellet durability, with sawdust binder at 10% and moisture content at 17% exhibiting the lowest durability at 78.0%. This deterioration occurred despite the fact that sawdust's lignin content of 38.1% was significantly higher than RH at 21.8%.

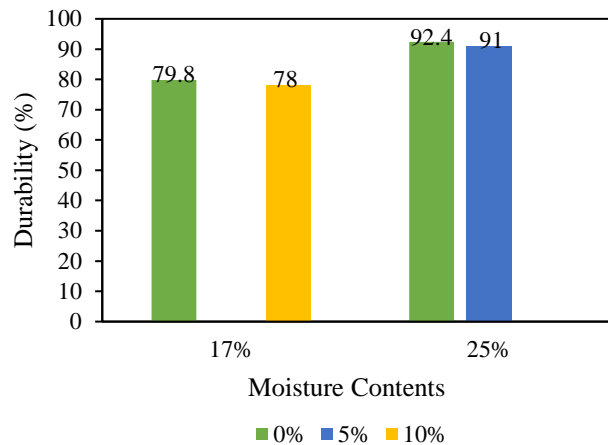


Figure 4. Durability comparison with and without sawdust.

One possible explanation for this occurrence was that sawdust had a low hemi-cellulose content of 7.5%, compared with RH (19.5%) and PKS (17.9%), as shown in table 4. Hemi-cellulose played an important role in storing moisture [13]. Low hemi-cellulose content meant that sawdust had less ability to store moisture, which acted as a binding agent to the RH pellets.

Figure 5 shows that RH pellets with 5% POME and 17% moisture improved pellet durability by 12.6% whereas the ones with 10% POME and 21% moisture deteriorated the pellet durability by 5.5%. This can be explained by understanding the fact that POME is a liquid. A larger amount of POME meant adding more moisture into the RH pellets. In this case, RH pellets with a recipe of POME/5/17 (Run 8) contained 21.9% moisture whereas those with POME/10/21 (Run 9) resulted in about 30.4% moisture. So, the durability of RH pellets was adversely affected by too much moisture.

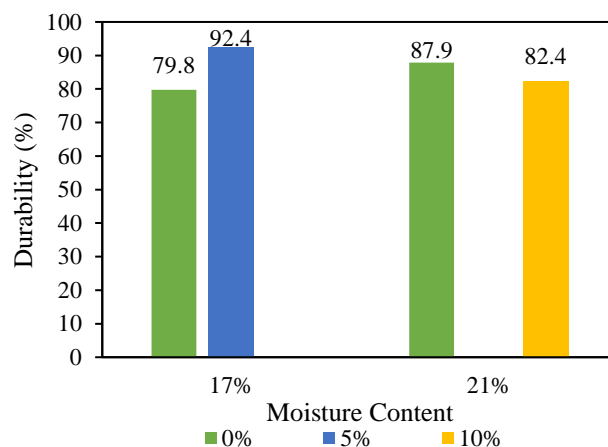


Figure 5. Durability comparison with and without POME.

Figure 6 shows the durabilities of RH pellets based on binder contents of 5% and 10%, and sorted according to binder types. For PKS, the durability improved from 92.2% for RH pellets with PKS/5/21 recipe (Run 2) to 94.9% for those with PKS/10/25 (Run 3) when PKS content increased by 5% and moisture increased by 4%. Upon a closer examination of the previous results (Refer Figure 3), adding 5% of PKS binder at 21% moisture content improved the durability by 4.3%. This is similar to adding 4% moisture content with 0% binder where the durability improved by 4.5%. On the other hand, adding 10% of PKS binder at 25% moisture content only improved the durability by 2.5%. This suggests that

binder addition may be a substitute for moisture addition. However, at higher moisture levels, the addition of binder becomes less significant for durability improvement.

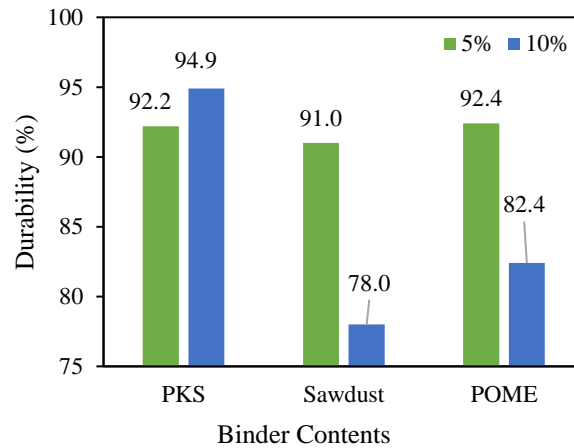


Figure 6. Durabilities at different binder contents.

When sawdust content increased by 5% but moisture reduced by 8% at the same time, the durability deteriorated from 91.0% for RH pellets with Sawdust/5/21 recipe (Run 5) to 78.0% for those with Sawdust/10/25 (Run 6). This effect can be understood by observing the results in Figure 4, which compares the durability for RH pellets with and without sawdust binder at 17% and 25% moisture contents. At 17% moisture content, adding 10% of sawdust binder deteriorated the durability by 1.8%. Interestingly, at 25% moisture content, adding 5% of sawdust binder also deteriorated the durability by 1.4%. The results were due to the low hemi-cellulose content of sawdust, in which a higher sawdust content lowered the sample's ability to absorb more moisture.

Finally, the durability deteriorated from 92.4% for RH pellets with POME/5/17 recipe to 82.4% for those with POME/10/21. As discussed previously, adding POME is akin to increasing moisture content. Therefore, increasing POME content could only improve pellet durability to a certain extent before the durability deteriorated.

3.2. Effect of moisture content

Figure 7 shows the mean durabilities of RH pellets at 17%, 21% and 25% moisture contents. It can be clearly seen that the durability increased as moisture content increased. This is because water is both a lubricant and a binding agent that helps generate van der Waals forces by increasing the surface area of the particles. This is true up to a certain extent before the reverse occurs when water is trapped within the particles [9].

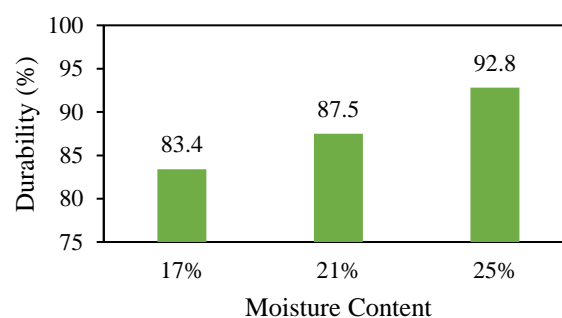


Figure 7. Mean durabilities at different moisture contents.

It should also be noted that RH pellets with PKS/0/17 recipe and those with Sawdust/10/17 performed poorly at 79.8% and 78.0%, respectively. A common denominator is the low moisture content at 17%. This suggests that the durability of RH pellets with solid binders could be improved at higher than 17% moisture. The higher limit of moisture content can be estimated from the results of RH pellets with POME/5/17 and POME/10/21 recipes comprising moisture contents of 21.9% and 30.4%, respectively. The former's durability of 92.4% was high, probably because the high moisture content of POME contributed as a binding agent in addition to the added water. As for POME/10/21, the durability of 82.4% shows that the high moisture content of 30.4% caused water to be trapped within the particles, which deteriorated the durability.

4. Conclusions and Recommendations

Palm kernel shell (PKS), palm oil mill effluent (POME) and sawdust were studied as potential binders that could improve durability of RH pellets. Results indicated that PKS and POME improved the RH pellet durability whereas the opposite was observed for sawdust. The influence of binder and moisture contents on pellet durability were also studied. Rice husk pellets with a 17% moisture content performed poorly, even with the addition of binders. Increasing pellet moisture contents from 17% to 21% and 25% resulted in higher durability, with 25% moisture producing the highest durability. Increasing binder contents also improved RH pellet durability but less significant as compared with increasing moisture contents. The highest durability achieved was 94.9% for RH pellets with 10% PKS and moisture content of 25%. However, this is still 2.6% below the target of 97.5% set by ISO.

In theory, a durability of 97.5% or higher could have been achieved for the RH pellets. Based on Taguchi method, it is predicted that RH pellets with PKS, 5% binder and 25% moisture content can achieve 97.8% durability whereas POME with 5% binder and 25% moisture content could achieve 97.9% durability. It is recommended to test this recipe as a future work. The influence of hemi-cellulose on pellet durability shall also be further studied as there are limited studies on this subject.

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